Thermal and Thermo-mechanical Characterization of Teeth and Their Restorative Materials by Open Photoacoustic Technique

J. L. Pichardo-Molina[1], G. Gutiérrez-Juárez[2], R. Huerta-Franco[2], M. Vargas-Luna[2], P. Cholico[3] and J. J. Alvarado-Gil[4]

[1] *Centro de Investigaciones en Óptica, Loma del Bosque 115, Col. Lomas del Campestre, C. P. 37150, León Gto. México*
[2] *Instituto de Física de la Universidad de Guanajuato, A. P. E-143, C. P. 37000, León Gto, México*
[3] *Dpto. de Clínicas Odontológicas Integrales, Centro Universitario de Ciencias de la Salud, Universidad de Guadalajara. José Maria Echaury y Juan Díaz Covarrubias, S/N. Col. Industrial, C. P. 44280. Guadalajara, Jal. México.*
[4] *Departamento de Física Aplicada, CINVESTAV-Unidad Mérida, Carretera Antigua a progreso, Km. 6, Cordemex, Mérida, Yucatán 97310, México.*

Abstract

Using the open photo-acoustic (PA) cell, we study the thermal diffusivity and the lineal expansion coefficient of teeth and three of their most common restorative materials (Amalgam Phase Alloy, Ionomer Fuji II LC, and Resin 3MFPITEK Lutine ™Z250). Also a theoretical simulation of PA signal for a two layer system tooth-restorative-material was done. The model takes into account the coupling of thermal waves and thermo-elastic vibration modes in both layers. Two cases were discussed: 1) when both layers present both diffusion and thermo-mechanical vibration, and 2) when only one of the layers presents thermo-mechanical vibration. In order to obtain information about the behavior of two layers system (teeth and restorative dental materials), a simulation of the PA signal was made.

1. INTRODUCTION

Health care is one of the most important subjects in our society, but some times much attention is paid on the esthetic appearance of the body. In recent years, the dentistry market has developed new materials to satisfy the requirements of health and esthetic of their customers. However, the first generation of these new composite materials were limited by low wear resistance to abrasion, color variation, increased polymerization shrinkage, low flexural strength, low modulus of elasticity, and high incidence of fracture. Newer formulations offer better advantages to ensure the results of the applicability in tooth restoration. New resins, amalgams and cements are used in actual days; however, the thermal and thermo-mechanical information is not always available for its right application.

Taking into account only the health aspect, the market of dentistry is mainly focused on durability and comfort. The matching of thermal, mechanical and thermo-mechanical properties, between teeth and their restorative materials, is one of the main concerns in this field. The study of these properties in new composite materials compared to those for teeth and the traditional amalgam is of the main importance for their use in teeth restoration. Also the characterization of these properties after teeth restoration has been performed, is a very important task.

Photoacoustic (PA) and related photothermal techniques have been used in a wide variety of fields for thermal and thermo-mechanical characterization. PA technique looks directly at the heat and pressure waves, generated in a sample, followed by the absorption of pulsed or modulated electromagnetic radiation. In the conventional PA experimental arrangement using microphone, the sample is enclosed in an air-tight cell and it is exposed to a modulated light. As a result of the periodic heating of the sample, the pressure into the chamber, which oscillates at the same modulation frequency, can be detected by the microphone coupled to the cell. The resulting PA signal depends not only on the amount of heat in the sample, but also on how this heat diffuses through the sample and to their surroundings. The Open Photoacoustic Technique (OPC) configuration has been developed as a suitable method for measuring the thermo-mechanical properties of solids looking at the bending phenomenon due to the temperature profile through the thickness of the sample. Using the OPC method, the thermal diffusivity, α_s, and the thermal expansion coefficient, α_T, of single layers can be obtained.

In this work, thermal and thermo-mechanical characterization of teeth and restorative material using the OPC technique is performed. The case of the system teeth-restorative material is theoretically modeled for the OPC technique. In this work, it was used a model, which takes into account the coupling of thermal waves and thermoelastic vibration modes in both layers.

2. THEORY AND EXPERIMENT

The OPC uses the heat transmission configuration, in this case, the sample is mounted directly onto the front sound inlet of an electret microphone and fixed with vacuum grease. The sound inlet is a circular hole of 3 mm diameter, and the front microphone chamber adjacent to the metallized face of the diaphragm is a cylinder of 7 mm of diameter and 1 mm long (Fig. 1).

The PA signal is generated by illuminating the sample with a modulated light beam. We used a 70 mW He-Ne laser (Melles Griot 05-LHP-928) modulated with a mechanical chopper (Stanford Research Systems SR540) and uniformly focused onto the sample. The signal from the microphone is sent to a Lock-in amplifier (Stanford Research Systems SR850). The signal amplitude and phase are both recorded as a function of the modulation frequency.

2.1 Single Layer System

For the transmission configuration, the model which takes into account the thermal diffusion and the thermo-elastic bending predicts that the output voltage of the microphone is given by [1].

$$V_{opc} = V_0 \left[\frac{j\omega\tau_E}{1 + j\omega\tau_E} \frac{\beta I_0}{T_0 l_g \sigma_g k_s \sigma_s} \right] \times$$

$$\left[\frac{1}{Sinh(l_s\sigma_s)} - \frac{3R^4 \alpha_T T_0}{2R_c^{\,2} l_s^{\,2}} \sqrt{\frac{\alpha_s}{\alpha_T}} \frac{(l_s\sigma_s/2)Sinh(l_s\sigma_s) - Cosh(l_s\sigma_s) + 1}{l_s\sigma_s Sinh(l_s\sigma_s)} \right], \tag{1}$$

where I_0 is the incident radiation intensity, V_0 is a constant dependent on the microphone characteristics, τ_E is the microphone response time, $j = \sqrt{-1}$, R_c is the radius of the chamber in front of the microphone diaphragm (R_c = 3.5mm), R is the support radius of the sample (R=1.5mm), l_i, k_i, α_i, and σ_i are the width, thermal conductivity and complex thermal diffusion coefficient ($\sigma_i = (1+j)(\pi f/\alpha_i)^{1/2}$) and i refers to sample and air gas media. β is the optical absorption coefficient and α_T the thermal expansion coefficient.

V_{opc} represents the PA signal which is obtained from two contributions, the first term represents the thermal diffusion contribution, whereas the second term is the thermo-elastic bending. Both contributions are expressed in terms of the modulation frequency. By fitting the experimental data for the OPC signal amplitude or phase, as a function of the modulation frequency to equation (1), the thermal diffusivity (α_s) and thermal expansion coefficient (α_T) can be obtained.

2.2 Two Layers System

In order to obtain information about the behavior of two layers system (teeth and restorative dental material), a simulation of the PA signal was made. The two layers model used here takes into account the thermal diffusion and thermo-elastic vibration, considering that thermal waves and thermo-mechanical vibration match perfectly at the interface of both layers. Moreover it is assumed that the mechanical properties (Young Modulus and Poisson Ratio) have similar values for both materials. An extensive analysis of this model was reported by Pichardo [1] where an extrapolated model of G. Rousset et al. [2] was studied. The PA signal for this model is given by:

$$V_{opc} = V_0 \left[\frac{j\omega\tau_E}{1 + j\omega\tau_E} \right] \times \frac{\delta P_{Term} + \delta P_{Dif}}{\gamma P_0} \mathrm{e}^{i\omega t}, \tag{2}$$

where

$$\delta P_{Term} = -\gamma C_1 \Pi \left\{ \frac{6}{l^2}\left[\alpha_{T1}\left(\frac{X_2\Sigma_1 + s(X_1 - 1)\Sigma_1}{\sigma_1} \right) + \alpha_{T2}\frac{\Sigma_2}{\sigma_2} \right] - \right.$$
$$\left. \frac{12}{l^3}\left[\alpha_{T1}\left((X_1 - 1)\frac{X_2}{\sigma_1^2} + s(\Sigma_2 - \sigma_1 l_1)\frac{\Sigma_2}{\sigma_1^2} \right) + \alpha_{T2}\left(\frac{X_2 + l_1\sigma_2\Sigma_2 - 1}{\sigma_2^2} \right) \right] \right\} (X_2\Sigma_1 + sX_1\Sigma_2)^{-1}$$

and

$$\delta P_{Dif} = -\frac{\beta I_0 \gamma P_0}{2 l_g \sigma_g k_1 \sigma_1 (\beta^2 - \sigma_1^2)} \left[\frac{k_1\sigma_1}{k_1\sigma_1\Sigma_1 X_2 + k_2\sigma_2\Sigma_2 X_1} \right],$$

with $\Pi = \frac{R^2 - r^2}{2}$, $X_i = \cosh(\sigma_i l_i)$, $\Sigma_i = \sinh(\sigma_i l_i)$ and i in the material 1 or 2.

2.3 Materials

The sample materials were obtained from molars of Holstein-Friesian cow (samples C1–C4) and from third molars of human subject (sample H1). Thin samples, less than 1mm of thickness, were sliced. To get thinner samples, around 300 to 400 micrometers, they were polished mechanically with sandpaper (ultra fine 600 grit). Finally, in order to obtain optically opaque samples in the region of 788 nm, samples were painted with a metallic paint. The paint layer was around 10 micrometers and it was assumed that it does not affect the measurements. Three different samples of restorative materials were prepared; Amalgam of 366μm (Phase Alloy), Ionomer sample of 267μm (Fuji II LC), and Resin sample of 366μm (3MFPITEK Lutine TMZ250), these samples were labeled Am, Io and Re respectively. For the Ionomer and Resin samples, foil aluminum of 10 μm was glued using thermal paste to get optically opaque samples.

3. RESULTS AND CONCLUSIONS

3.1. One Layer Model

One sample of human and four samples of cow teeth were thermally and mechanically characterized using a modulation frequency range from 80 to 400 Hz. This frequency range was chosen because none of these contributions dominate. If the frequencies were less than 80 Hz, the thermal diffusion starts to dominate, on the other hand, if the frequencies were higher than 400 Hz, the thermo-elastic phenomenon dominates. In Fig. 2, the experimental data as a function of the modulation frequency of sample H1 and C3 are shown with full circles and the continuous line is the best fit to Ec. (1). The same procedure was carried out with all samples. In the case of the dental restorative material, the frequency region for analysis was from 80 to 800 Hz. In Fig. 3, the PA signal for the dental materials are represented by full circles, while the continuous line represents the best fit to Ec. (1). The values of α_s and α_T obtained for all samples are show in Table 1.

Table 1.

Sample	l_s (μm)	α_s (10^{-2} cm^2/s)	α_T (10^{-6} K^{-1})
H1	466	0.74	8.02
C1	466	0.78	12.79
C2	480	0.53	6.27
C3	376	0.51	4.50
C4	414	0.60	5.10
Re	267	0.25	16.46
Io	365	1.09	10.83
Am	384	1.60	34.08

Even if the mechanical properties (Young Modulus and Poisson Ratio), have similar values for both materials, the thermal compatibility should be carefully analyzed.

3.2. Two Layers Model

In Fig. 4, it is shown the theoretical results for the amplitude of the PA signal for teeth and two layer systems composed by teeth and a restorative material (amalgam, resin and ionomer). In each case the total thickness of the samples were 600 μm, in the two layers cases the thickness of the dental material was 500 μm and the thickness of the restorative material was 100 μm. The values for the thermal conductivity were taken from literature [3,4]: k_H=0.006, k_A=0.225 W/cm K, k_R=0.0015, k_I=0.006 (all in W/cm K). The values for the thermal diffusivity and linear expansion coefficient were taken from Table 1 for all the materials.

The PA signal amplitude shows a resonance, which is due to the presence of the thermoelastic bending. This resonance changes in the case of two layer system, taking into account that in this region both contributions are present with similar strength. These results show that the OPC technique can be used to study the thermal compatibility of dental material with the restorative material in two layer system configurations.

REFERENCES

1. J.L.Pichardo, PhD thesis, CINVESTAV-Unidad Mérida, México 2000.
2. G.Rousset and F.Lepoutre, *J. Appl. Phys*. **54**:2383 (1983).
3. D.E.Grenoble, and J.L.Katz, *J. Biomed. Mater. Res.* **5**:489 (1971).
4. http://www.lib.umich.edu/libhome/Dentistry.lib/Dental_tables/Coefthermexp.html

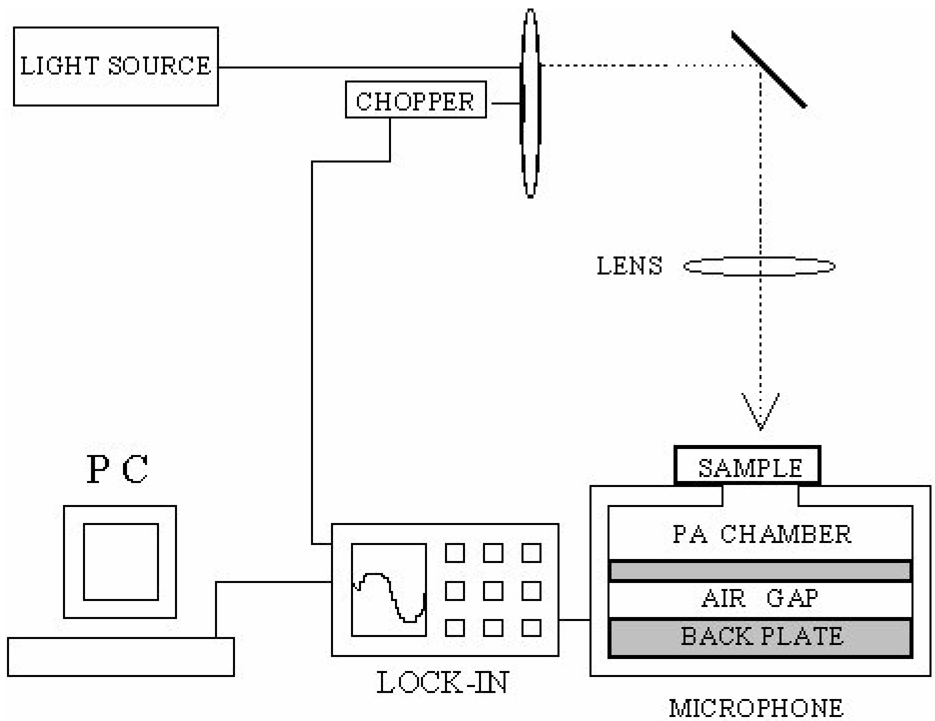

Fig. 1. Experimental Setup.

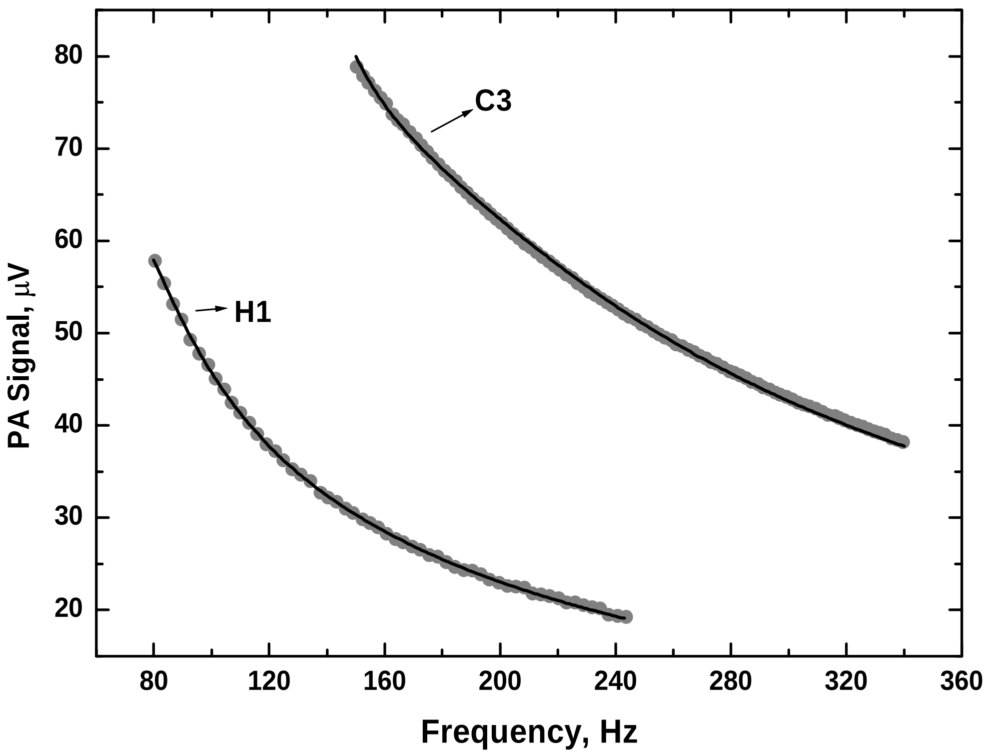

Fig. 2. Experimental data as a function of the modulation frequency of sample H1 and C3. The full circles are the experimental data and the continuous line is the best fit to Ec. (1).

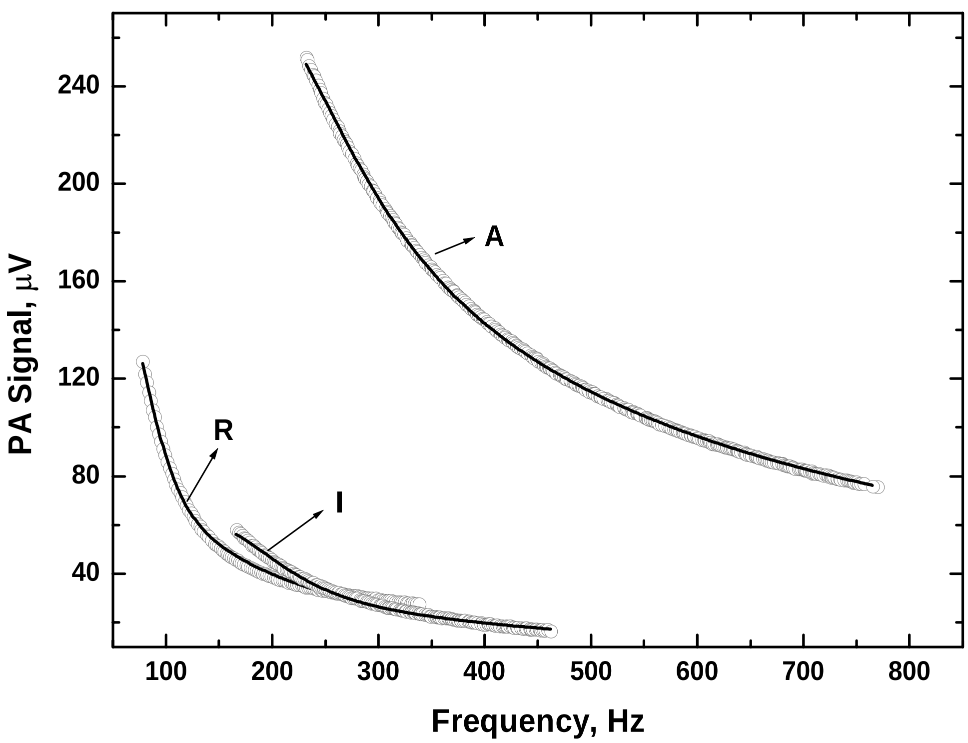

Fig. 3 PA signal for the dental materials are represented by full circles where A, R and I are the data for amalgam, resins and ionomer respectively), while the continuous line represents the best fit to Ec. (1) in each case.

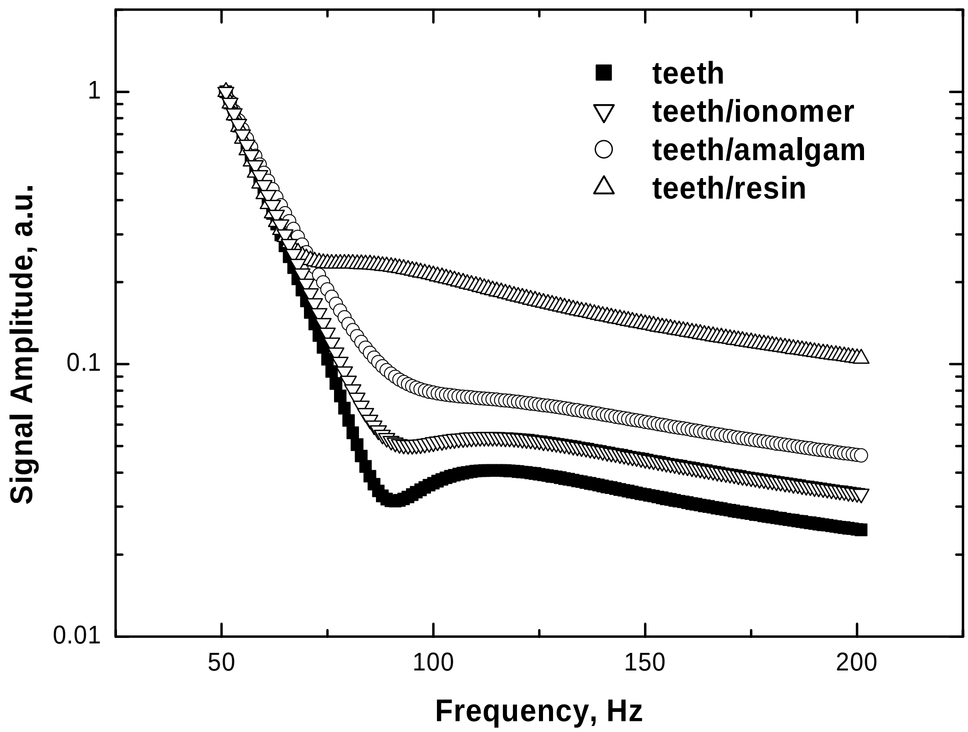

Fig. 4 Theoretical results for the amplitude of the PA signal for teeth and two layer systems composed by teeth and a restorative material (amalgam, resin and ionomer).